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ABSTRACTS

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AND

OTHER COMBUSTION/EXPLOSION RELATED RESEARCH held

on   22 - 24 JANUARY 1979 at

FORT WALTON BEACH, FLORIDA.

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COMBUSTION INSTABILITY	PARTICLE DYNAMICS	

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The report consists of a collection of abstracts of the numerous research progress reports given by AFOSR contractors and of invited papers from other governmental agencies and CONUS and European contractors. These papers presented over a three day period composed the annual contractors meeting on combustion dynamics associated with fuel-air explosions and other explosion related phenomena. The principal investigators and their organizational association are also identified.

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22-24 January 1979
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DIMENSIONS OF FAE CLOUDS
WHEN GENERATED BY HIGH EXPLOSIVES

Yves de Longueville

SNPE
Centre de Recherches du Bouchet

Under the auspices of the French Ministry of Defense (Service Technique des Poudres et Explosives), the "Societe Nationale des Poudres et Explosifs" (SNPE) has performed, during the last years, many experiments in order to get the main dimensions of fuel-air explosive clouds generated by the bursting effect of a high explosive enclosed in the fuel canister. Some parameters have been investigated, mainly concerned with the design of the canister:

- The volume of the canister containing the fuel, which is in practice propylene oxide (P.O.), extending from 10 to 300 liters.

- The mass ratio between the bursting charge and the fuel, for values of 1/100, 1/50 and 1/20.

- The nature of the high explosive used as the bursting charge, which may be an ammonium nitrate explosive or two kinds of poured PBX.

- The notion of the canister, which could be initially at rest or falling from a cable at a speed of 20 m/s.

- The air temperature during the cloud formation process.

Some other parameters have been occasionally investigated, dealing with the nature of the canister alloy, its wall thickness, its length/diameter ratio...

According to the pictures recorded using a framing camera at a frequency of 3000 to 3500 frames per second, the fuel motion can be described as a sequence of two phenomena:

A first phase showing a very fast expansion of the liquid contained in the canister, essentially characterized by a Gurney-type energy transfer.

A following phase, occuring a few tenths of a millisecond after the bursting charge detonation, and consisting of a slow evolution of the cloud dimensions which can be defined by the average values of height and diameter as functions of time.

The main results obtained are correlated with the mass ratio, the volume of the canister, the air temperature. Cloud dimensions are almost unaffected by a limited canister speed. Blasting effect of the cloud when detonated seems to be modified by a shift of the time delay between burst and detonation.

DETONATION IN GASEOUS C_2H_4O-air and C_2H_4-air mixtures
INFLUENCE OF METAL POWDER SUSPENSION
CONTRACTS D.R.E.T. FRANCE

M. GILTAIRE, J.WINTER
CENTRE D'ETUDES ET RECHERCHES DES
CHARBONNAGES DE FRANCE - CREIL -

B. VEYSSIERE, R. BOURIANNES, C.BROCHET,N.MANSON
LABORATOIRE D'ENERGETIQUE ET DETONIQUE-POITIERS-

I- Experiments were carried out on detonating gaseous mixtures of ethylene-oxyde and air to investigate the critical-minimum volume and ignition energy. Using an initiation charge of 100g. of dynamite the detonability range of the mixtures lies from 4-5 % to 25-30 % of C_2H_4O by volume. The detonability range increases when 2 charges of 100 g. dynamite or single charge of 600 g. were used.

The detonation of the mixture containing 10% of fuel was obtained in a 3 cubic meter plastic bag by using only one detonator consisting of an aluminium tube and 0.8g. of compressed P.E.T.N.

Using 5 m. of winding detonating fuse with a lead coating, containing only 2 g. of explosive per m., the explosion of the gaseous mixture turned into a detonation only when half the fuse length had detonated.

II - In the suspension of Al particles (mean particle size = 10 μ, concentration 30 g/m3), the detonation of the gaseous base-mixtures of ethylene and air, and ethylene-oxide and air was studied in a vertical tube of 69 mm diameter and 6 meters height. The initial conditions of the detonating mixtures were : pressure=1 bar, temperature =293 K and equivalence ratio = 1.15. The study demonstrates:

(i) the combustion of Al particles is initiated behind the detonation front apparently with an ignition delay of 10-70 μs ;

(ii) the duration of combustion of Al is in the order of few hundred μs ;

(iii) the unburned proportion of Al is lower than 10 % ;

(iv) in the presence of Al, the detonation velocities of the base-mixtures reduce by about 3 % and the detonation pressure profiles p(t) get significantly modified.

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AN OVERVIEW OF BRITISH RESEARCH AND DEVELOPMENT
INVESTIGATIONS ASSOCIATED WITH UNCONFINED FUEL-AIR EXPLOSIONS

by

Joeff Hooper
Defense Research Staff
British Embassy
Washington, D. C.

ABSTRACT NOT AVAILABE

AN OVERVIEW OF U. S. NAVAL WEAPONS CENTER RESEARCH
DEVELOPMENT ACTIVITIES ASSOCIATED WITH
UNCONFINED FUEL-AIR EXPLOSIONS

by

James Bowen and Larry Josephson
Naval Weapons Center
China Lake, California

ABSTRACT NOT AVAILABLE

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AFATL COMBUSTION DYANMICS RESEARCH AND DEVELOPMENT PROGRAM
AND
FUTURE REQUIREMENTS ASSOCIATED WITH CONVENTIONAL WEAPONS

by

AFATL/DLA (M. Zimmer)
Eglin AFB, Florida

ABSTRACT NOT AVAILABLE

U. S. ARMY SUPPORTED RESEARCH AND DEVELOPMENT
AND
FUTURE REQUIREMENTS IN UNCONFINED FUEL-AIR EXPLOSIONS

by

N. Slagg, B. Fishburn and P. Lu
USA ARRADCOM
Dover, New Jersey

ABSTRACT NOT AVAILABLE

6

FIELD TESTS ON INITIATION AND DETONATION
OF REACTIVE FUEL-AIR CLOUDS

by

I. Isaacson, E. P. Marram and P. P. Ostrowski
Geo-Centers, Inc.
Newton Upper Falls, Massachusetts

ABSTRACT NOT AVAILABLE

DIAGNOSTIC TECHNIQUES AND INSTRUMENTATION
FOR
REMOTE MEASUREMENT OF CHARACTERISTICS OF CHEMICAL CLOUDS

by

I. Isaacson, E. P. Marram and P. P. Ostrowski
Geo-Centers, Inc.
Newton Upper Falls, Massachusetts

ABSTRACT NOT AVAILABLE

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DETONATION OF A SPRAY DELIVERED FUEL-AIR
CLOUD ON THE EXTERIOR OF A BUILDING

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A large building was recently destroyed in a feasibility demonstration at the BRL using a spray-generated fuel-air explosion delivered by a flame thrower tank. The technical approach had been validated before by the Air Force Armament Laboratory. Behind such a test is Army concern that as countrysides become more developed, any future conflicts will unavoidably spill over into builtup areas. Tanks are presently relatively ineffective in cities since available Army rounds have not been optimized to attack buildings. The results of the firing test described here raises the possibility of increasing tank lethality in cities by equipping special tanks with a spray generating fuel-air device.

The cloud of fuel was sprayed from a modified unmanned flame thrower tank. In four seconds the nozzle dispersed 100 pounds of propylene oxide into a cloud 100 feet long, 10 feet high, standing a foot off the front of the building. Three hundred milliseconds after spray cutoff, the explosion was initiated by firing two each, one pound high explosive charges preemplaced to be inside the cloud. The building's dimensions were 40x20x16 feet, wooden framework covered by asbestos board. The fuel-air explosion left no identifiable framing members except for the floor joists. Good blast records were obtained which indicate the loading on the building and the environment inside the tank itself.

The measurements show that a tank crew would not have been hurt if hearing protectors were used. The test results indicate that a massive overkill of the structure took place, indicating the desired effect could be produced with less fuel sprayed.

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DICE-FAE ANALYSIS OF FUEL DISPERSAL AND DETONATION
FROM A FUEL- AIR-EXPLOSIVE DEVICE (F08635-76-C-0082)

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Liquid FAE (Fuel-Air-Explosive) devices are weapons which disperse a liquid fuel into a relatively extensive cloud using a small explosive charge. After the cloud has expanded enough to provide a suitable fuel/air mixture ratio, it is detonated. The fuel is initially contained in a canister with the dispersing explosive (burster charge) at the center. The detonation of the cloud (usually referred to as the second event, or SE) is initiated by one or more small explosive charges injected into the cloud. Ideally, the dispersed fuel should be totally consumed in the FAE detonation. Fuel-rich areas (in which some of the fuel doesn't burn because the oxygen is exhausted) or fuel-lean areas (with low fuel/air ratios) within the cloud are undesirable.

The purpose of our study was to develop and use physically based numerical simulation models to examine the cloud dispersion and cloud detonation (second event) aspects of a specific FAE event. The fuel mass densities and particle size distributions, as well as the induced air pressures and velocities, are the principle parameters of interest.

The basic numerical code used for the FAE analysis was DICE, a 2-D implicit Eulerian finite difference technique which treats fluid-particle mixtures. DICE treats particle size groups which can flow independently through the Eulerian grid. Mutual momentum and thermal interactions between the particles and the gases are treated through drag and heat exchange models. Phase changes (solid-liquid-vapor) can take place.

For application to FAE analyses, adaptations were made in the basic DICE code to allow treatment of, (1) stripping or breakup of liquid drops into smaller droplets as they are acted on by aerodynamic forces, and (2) burning of the fuel, with development of a detonation wave if the local energy release rate is sufficiently high.

Using the DICE-FAE code, solutions were generated of both the fuel cloud dispersal and detonation phases for an FAE device, the BLU-73. The cloud dispersal analysis started with initial conditions representing the fuel mass and burster products just after canister breakup, and followed the subsequent cloud dispersal until 60 msec.

The cloud detonation analysis started with the cloud characteristics at 60 msec and with second event initiation by a centrally-located explosive charge at that time. This analysis extended through cloud detonation and to 77 msec.

The principal results and conclusions are summarized in the following paragraphs:

(a) *The flow field within the expanding fuel cloud leads to severe variations in the fuel density.* Figure 1 shows the air velocity field at 30 msec. Rapid radial expansion of the fuel mass near the meridian plane of the device causes vortices to form above and below this plane. Figures 2 and 3 show the total fuel density along planes or surfaces which pass between and through the vortices. Fuel within the vortices cannot escape because of the circular flow. Consequently, these are regions of high fuel concentration. Fuel between the vortices is swept to larger radii by the rapid flow. This causes an accumulation of fuel at the larger radii, forming a third region of high fuel concentration. Large fuel (vapor and liquid particles) gradients persist to the end of the dispersal phase.

(b) *Cloud dimensions predicted by DICE-FAE at the end of the fuel dispersal phase compare favorably with experimental observations.*

(c) *Fuel drop breakup by aerodynamic shattering is effective in reducing all but the very largest fuel drops to small droplets.* Figure 4 plots the time-history of distribution of fuel mass in drops of different size ranges (and in fuel vapor). By 10 msec all fuel drops with initial diameters smaller than 1 cm have been completely shattered into 0-0.2 cm droplets (.01 mean particle size). At the time of the second event initiation (60 msec) 90 percent of the fuel mass in the cloud consists of 0-0.2 cm droplets. About 3 lbs. of the fuel has impacted the ground.

(d) *A relatively large, centrally-located second event initiator charge is required to detonate the cloud, since fuel concentrations near the axis are relatively low at 60 msec.* A 70 gm initiator proved inadequate, and the detonation would not propagate through the cloud. A 350 gm initiator was then used, and the cloud was successfully detonated in the numerical simulation.

(e) *During cloud detonation, fuel droplets are first vaporized as the detonation shock arrives; detonation then occurs until the locally available fuel or oxygen is exhausted.* The portion of Figure 4 after 60 msec shows the rapid vaporization of fuel droplets during the period from 60 to 63 msec. The detonation is complete by about 67 msec.

(f) *The maximum pressure experienced on the ground during the FAE detonation was 200 psi at about 10-ft. radius; impulse delivered to the ground was a maximum at the axis and dropped sharply with increasing radius.*

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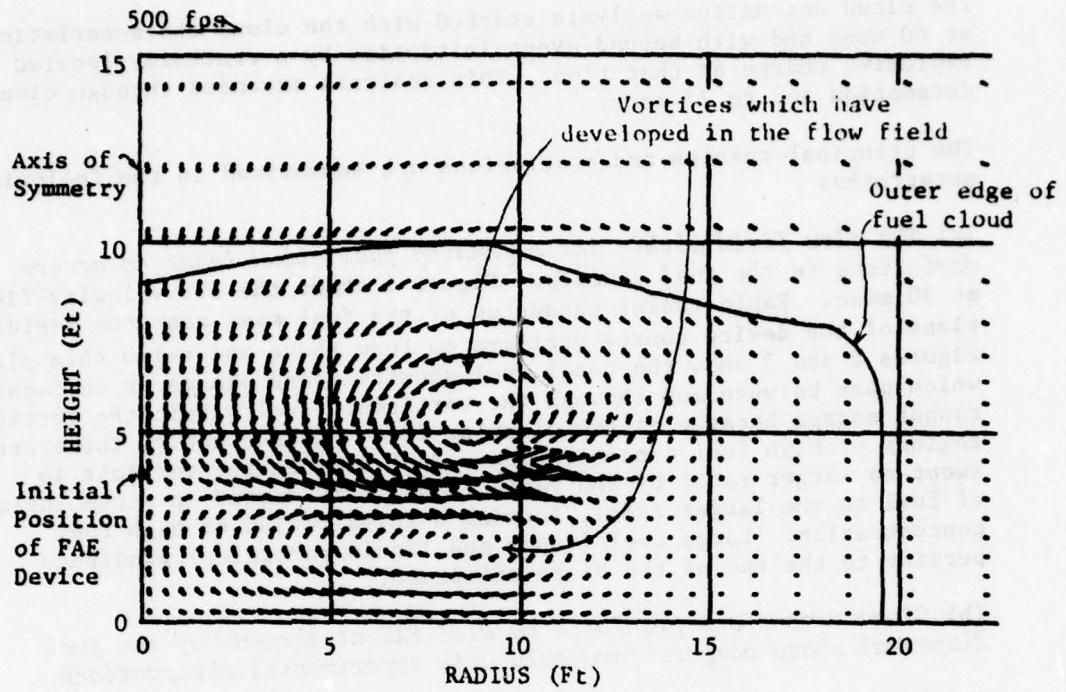
Figure 1. Air Velocity Vectors in Fuel Cloud at 30 msec
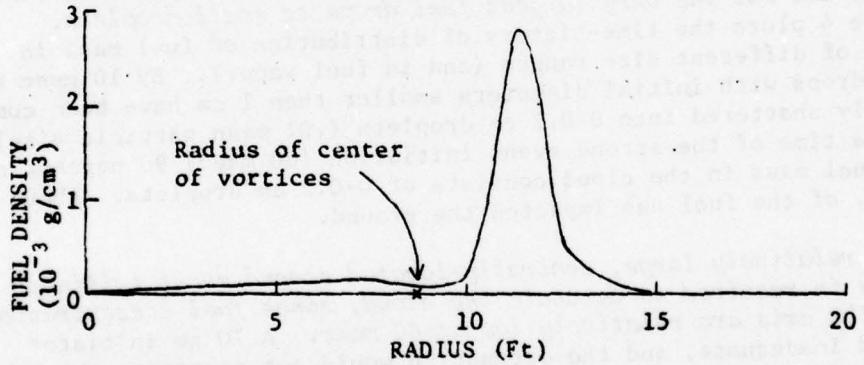
Figure 2. Total Fuel Density versus Radius at 3.8-ft Height
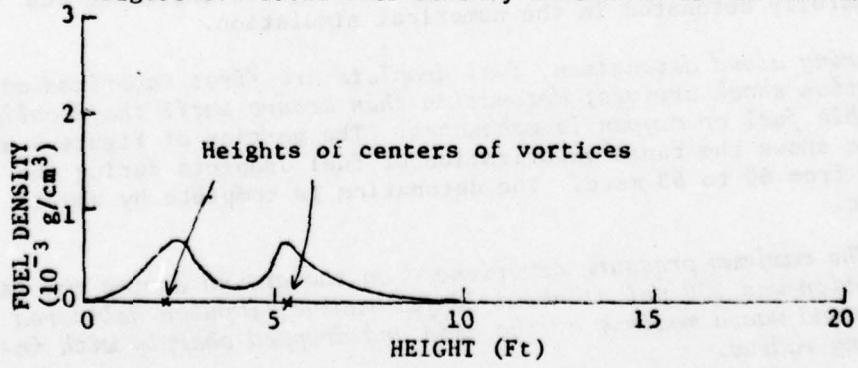
Figure 3. Total Fuel Density versus Height at 8.75-ft Radius

Dispersal Phase — **Detonation Phase**

Initial fuel mass – 72 lbs

0 – 0.2 cm drops – The mass in this small drop group increases rapidly due to the breakup of larger drops. After ~10 msec, almost all fuel consists of small drops and vapor

Fuel drops in these groups are quickly shattered by aerodynamic forces

0.2 – 0.75 cm drops

0.75 – 1.0 cm drops

1.0–25 cm drops

Fuel vapor—gradually increases during dispersal phase due to evaporation

Small drops rapidly vaporize as they are engulfed by detonation shock

Amount of fuel vapor initially increases as drops vaporize, then decreases as vapor burns

About 12% of initial fuel mass remains (as vapor) due to sub-optimum distribution in fuel-rich regions

Second Event Initiation

FUEL MASS (Lb)

80

60

40

20

0

TIME AFTER BURST (msec)

0   20   40   60   80

Figure 4. Distribution of Fuel in Different Droplet Sizes and as Vapor

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UNCONFINED VAPOR CLOUD. EXPLOSION STUDY

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The United States Coast Guard is charged with insuring the safety of the marine transportation mode, including the protection of those not directly involved. This problem has become more difficult in recent years with the increasing shipment of hazardous materials. One of the commodities of special and increasing interest is Liquefied Natural Gas (LNG). As early as 1968 the Coast Guard began studying this material, and in 1973 we began our Unconfined Vapor Cloud Explosion Study (UVCES), at the Naval Weapons Center, China Lake, California.

Why is the Coast Guard interested in unconfined vapor clouds? Probably for the same reason as the Air Force is interested — a vapor cloud of a detonable vapor is very dangerous to people and property because the oxidizer is available "for free" from the air, when properly mixed. Despite the fact that the Coast Guard wants to prevent the detonation and the Air Force to cause the detonation, they both must first learn what factors favor detonation. Accidental Liquefied Petroleum Gas (LPG) spills have resulted in unconfined detonations and with the very large quantities of LNG carried in a single ship, often five tanks of 25,000 m^3 each, the consequences from an accidental LNG spill followed by detonation would be severe.

The UVCES has been centered around methane and LNG as fuels. To our knowlege these have not been tested in Fuel-Air Explosives and, therefore, our work should be of interest to the Air Force and others involved in FAE work. Our program is best understood by examining each part in detail.

The first major group of experiments simulated unconfined vapor clouds with a gas-air mixture confined by thin transparent plastic hemispheres 10 m and 20 m in diameter. Low energy spark igniters failed to detonate methane-, propane-, ethylene oxide-, ethylene-, acetylene-, or butadiene - air mixtures. Obstacles in the cloud failed to significantly accelerate the flame front, but a partially enclosed instrumentation channel did accelerate the flame front somewhat. Vertical flame velocities were greater than the horizontal, but there were no measurable overpressures.

To directly initiate an unconfined cloud to detonation a high explosive, Composition B, was used in 10 m diameter hemispheres. The dependence of a cloud's ability to detonate on the composition of the cloud is illustrated by the failure of 2 kg charges to detonate either 100% methane - or 90% methane - 10% propane - air mixtures; 85% - 15%, 70% - 30%, and 60% - 40% did detonate. An earlier test at 1.35 kg also failed to detonate 100% methane. Finally, a test using a 22 kg charge is scheduled, the size of the initiator suggested by the work of Bull and Martin of Shell, U.K.; one additional test is scheduled, with a larger charge if detonation fails and a smaller one if it succeeds.

Another set of experiments uses a planar wave detonation to initiate an unconfined methane detonation in a 20 m diameter hemisphere. A 2.4 m diameter tube 6.1 m long will be placed vertically into the bottom of the test site with the opening at the center of the hemisphere's base. Sheet explosive at the tube bottom will generate a planar detonation. Will the planar wave transform into a spherical detonation wave?

In support of the unconfined detonation work, methane, propane, and ethylene oxide were deflagrated and detonated in a shock tube. Pressures and velocities were measured.

Dual Fuel-Air Explosives (FAE) will be used, with a propylene oxide FAE as the initiator and an LNG FAE as the test subject. Here a planar detonation wave serve as initiator. Geo-Centers will perform this work at Sadia.

Finally, worth mentioning are the LNG and LPG spill tests on water, in which pool fires and cloud fires were run, with spill size of up to 5.7 m^3. For the cloud burns there were no flame accelerations noted.

Much of the Coast Guard's UVCES should be of value to the Air Force.

MATHEMATICAL MODELING OF UNCONFINED
FUEL-AIR EXPLOSIONS

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The achievement and maintenance of detonation in fuel-air clouds
is sensitive to several aspects of both cloud and initiator char-
acteristics. These factors imply trade-offs between dispersal
and igniter systems and payload in the engineering of a reliable
large fuel-air explosive (FAE) weapon. Analysis of data from this
laboratory identifies the critical dependences to be on cloud
stoichiometry and structure, as well as on initiator geometry and
timing. For the subject fuel--90% CH_4:10% C_3H_8--these factors
combine to preclude accidental detonation even though its detona-
tion by a mere three pounds of Comp B has been achieved in the
laboratory. For more potent fuels, engineering an FAE weapon must
consider these effects. Here the results of our studies of detona-
tion of natural gas/air clouds and their implications for FAE
weapon design are presented.

The data analyzed are the results of numerical experiments using
validated mathematical models of the direct initiation of uncon-
fined detonation in gaseous $CH_4/C_3H_8/O_2/N_2$ mixtures. These models
simulate the inviscid reacting compressible flow processes
involved through the application of finite difference Lagrangian
hydrodynamics and multistep finite rate chemical kinetics. Using
rate data from the literature, these models have quantitatively
accounted for measurements on a variety of systems, so their
results may be regarded as sound extrapolations of experimental
results.

The design parameter trade-offs are dominated by the stoichiometry
dependence of the detonation threshold. The model results show a
narrow range of detonable mixtures near stoichiometric. This
implies a severe initiator weight penalty associated with nonideal
dispersal or improper event coordination.

Nonideal dispersal has two aspects: composition outside the
detonation limits which prohibits establishment of detonation, and
local concentration variations which quench it. The above results
bear directly on the first point, and are an important aspect of
the second effect. For large clouds, the duration of the energy
release affects the detonation threshold. Models of shock initia-
tion of detonation demonstrate a

$$E \propto t^{11/4}$$

threshold scaling; this is tantamount to a further increased energy requirement for detonation maintenance through less detonable striations in the cloud.

The systematic study of direct initiation of unconfined detonation in a single fuel-air cloud type highlights FAE weapon design considerations. Disperser/igniter requirement relations are shown to merit special attention.

DETONATION OF UNCONFINED HETEROGENEOUS FUEL-OXIDIZER PARTICLES
DISPERSED IN AIR

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Current emphasis in fuel-air explosive (FAE) technology is on
the use of solid fuel particles and the elimination of the sec-
ond-event requirement. This paper will describe several concepts
that have been investigated at IIT Research Institute under our
Internal Research and Development programs.

FAE is presently a two-step process: an explosive burster dis-
perses the fuel into a suitable fuel-air cloud, then a second-
event explosive, activated within an easily-detonable region of
the cloud, initiates detonation of the entire fuel-air cloud.
A single-event FAE can be produced by the simultaneous dispersal
and detonation of the fuel-air cloud as it is being formed. Al-
ternatively, a spontaneous FAE can be achieved by dispersing a
pyrophoric fuel into an appropriate fuel-air cloud within the
ignition induction period. We have investigated both of these
concepts with some success, but our major effort was directed at
a concept best described as a one-step automatic two-event FAE.
Here the second-event explosive is replaced by a very highly
hypergolic oxidizer under the implosive dispersal mode. The
technique is a one-step process since only one explosive charge
need be detonated. The mechanism, however, proceeds via two
events as the explosive charge causes a dual dispersal: (1) the
fuel is dispersed into a fuel-air cloud immediately and (2) the
hypergolic oxidizer is dispersed somewhat later, after the
implosion compression is relieved. It must be noted that for a
true FAE to occur the fuel must be dispersed appropriately in
air. This requires a small but finite amount of time. Whether
the subsequent fuel-air detonation is achieved spontaneously,
as in the case of pyrophoric fuels, or automatically, utilizing
this implosion mechanism, a second event is nevertheless neces-
sary. Automatic detonation requires only a small amount of
hypergolic oxidizer, just enough to initiate the detonation
of the fuel-air cloud.

Experimental efforts to achieve one-step FAE using the implosive
technique for driving a hypergolic oxidizer into explosively
dispersed fuel resulted in qualified success. The resultant
fuel-oxidizer reaction did produce a supersonic flame front
with associated shock-wave output. The velocity, however, was
rather low – about Mach 2 – and probably inadequate to initiate
the associated fuel-air detonation which has been shown to pro-
ceed at about Mach 6. Furthermore, the implosion process with
the particular device used allowed a time interval of 4 to 5
msec between fuel dispersal and subsequent oxidizer dispersal.

This proved to be about an order of magnitude less than required. In addition, the aluminum powder that was used did not disperse adequately, so a stoichiometrically adequate fuel-air cloud was not achieved. We are presently evaluating techniques that may extend this time delay by about an order of magnitude. In our experiments, about 400 g of hypergolic oxidizer, an interhalogen, was placed in a steel lecture bottle, then wrapped with about 400 g of Detasheet explosive. This item was then centered in a cannister containing about 5 kg of aluminum or liquid hydrocarbon fuel.

Our efforts to achieve a one-step FAE using the implosion technique to drive a hypergolic oxidizer into explosively-dispersed fuel produced less definitive results. We demonstrated that a supersonic flame front between the dispersed fuel and the hypergolic oxidizer components can be achieved, hence a detonation can be obtained. It appears, however, that the velocity of the induced detonation is controlled, if not limited, by the dispersal velocity of the implosively dispersed oxidizer. Whether or not a sufficiently strong shock wave can be obtained in this manner to propagate detonation into the remainder of the fuel-air cloud remains to be determined. There is, certainly, ample energy output from the fuel-oxidizer reaction, which is about twice as energetic as the detonation of typical high explosives of comparable weight. Initiating the detonation of fuel-air clouds in this one-step mechanism will require further theoretical and experimental studies.

STUDIES OF DISTRIBUTED HETEROGENEOUS FUEL-AIR EXPLOSIONS

ABSTRACT

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The calculation of blast effects from distributed fuel-air explosions is considerably different than that for condensed nondispersed explosives. In particular, the detonation wave itself can engulf target structures due to the large scale of the FAE system. The geometry and scale of FAE and method and location of initiation contribute to highly directional blast effects and complex wave unloading systems. These effects have been witnessed in accidental vapor cloud explosions as well as military testing.

Two-dimensional hydrodynamic codes have been exercised for FAE but are of limited usefullness since idealized, rotationally symmetric ignition sources are mandatory. They have shown, however, that the air-blast is very rapidly attenuated as it propagates beyond the FAE boundary.

Results will be presented in this paper summarizing a series of one-dimensional blast wave transient calculations that can be used to estimate the blast unloading characteristics of end and side (top) boundaries of FAE systems. Planar, cylindrical and spherical configurations are considered. The general phenomena examined include (1) normal and oblique reflection of a detonation wave with a rigid boundary, (2) forward, rearward and sideward transmitted air shock waves in the near field, and (3) interaction of detonation at a concentration discontinuity. Several special problems and side unloading effects (2-D quasi-steady flow) are also examined.

BLAST WAVE INITIATION OF CYLINDRICAL
GASEOUS AND HETEROGENEOUS DETONATIONS

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Abstract

A laboratory scale apparatus has been used to study the
initiation and propagation of gaseous and heterogeneous detona-
tion waves in a cloud of cylindrical geometry. The apparatus, a
sectored shock tube, corresponds to a 20 degree sector of a
cylindrical cloud. The radius is 140 cm and the cloud height
5.2 cm. In the heterogeneous case, the liquid fuel drops are
produced by perturbing the fuel flow to an array of needles at
the Rayleigh frequency. A cylindrical blast wave is transmitted
into the combustible cloud through activation of a blasting cap
and a condensed explosive. The progress of the resultant reacting
wave through the chamber is monitored by fast response pressure
switches. In some cases high speed framing photography is used.

The gaseous detonation studies are concerned with the possi-
bility of natural gas-air clouds undergoing detonation under
conditions of no confinement. Towards this end, a sequence of
experiments on the threshold energy requirements for the direct
initiation of detonation in stoichiometric methane-oxygen-nitrogen
mixtures is described and the results presented. In addition,
some results are presented for the case of stoichiometric methane-
ethane-air mixtures.

An ongoing supporting analytical study is briefly described
which treats the blast wave initiation criteria problem in an
approximate manner. A two discontinuity model is used which con-
sists of a shock wave and a reaction front, where they are sepa-
rated by an induction zone. Comparison of the predictions of this
model with available experimental results is made.

Results are also presented for the heterogeneous mixture case.
The decay of a cylindrical blast wave (with no reaction) through a
cloud of uniform size drops is compared to the case without the
drops. Experiments relating to the detonation of kerosene-air,
kerosene-oxygen, kerosene sensitized with NPN, and heptane-oxygen
are described and results presented. In addition, results are
presented wherein part of the cloud is devoid of fuel. High speed
framing camera records of heterogeneous detonation are also shown.

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LASER INDUCED COMBUSTION OF FUEL DROPS

E. K. Dabora

University of Connecticut

The experiments which will be described in this presentation have been prompted by the observed explosive reactions of fuel drops in the reaction zone of spray detonations. Such explosive reactions are usually noted in hydrocarbon sprays in oxygen. In order to delineate some of the conditions under which this type of reaction is possible, experiments on single droplets were conducted in quiescent atmospheres of either air or oxygen.

In each experiment a drop (~ 1.5 mm) hanging from a wire is subjected to a ruby laser beam. The laser can be operated in either the Q-switched mode or the pulsed mode and in most of the experiments the original laser beam is split in two beams which are focused from opposite directions on the droplet. The resulting phenomenon is observed interferometrically and monitored by a pressure transducer placed at 5 cm below the droplet.

It was found that when the laser is operated in the Q-switched mode, the droplet (propyl-nitrate or heptane) appears to break up or evaporate without ignition; however, a blast wave due to energy addition via gaseous break down is always present. When the laser is operated in the pulsed mode with two pulses at 100 μsec apart, the first pulse serves to break up the drop and the second to ignite it. In this case explosive combustion is often observed in oxygen whereas a non-explosive ignition takes place if air is used.

Data gleaned from the photographs on the rate of expansion of the droplet and therefore the extent of mixing will also be presented.

Fundamental Mechanisms of Unconfined Detonation
of Fuel-Air Explosions
(AFOSR 3207-77)
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Conventional means of initiating a detonation in an uncon-
fined fuel-air cloud is via a concentrated solid explosive charge.
This results in a two event process of first fuel dissimination to
be followed by detonation initiation by the trailing initiation
charge. If unconfined detonations can be initiated chemically,
then it may be possible to have a single event process of simulta-
neous dispersion of both fuel and the initiating chemical into the
atmosphere with subsequent detonation following a certain induc-
tion period when the primary initiating reactions have generated
sufficient free radicals for the secondary explosive oxidation of
the fuel-air cloud. The single event process is undoubtedly far
more reliable and the new generation of FAE devices based on this
single event concept are referred to as FAE III. Since 1975 the
Shock Wave Physics Group at McGill has been devoting a progres-
sively increasing amount of effort in demonstrating the feasibi-
lity of the single event concept of initiation. It seems appro-
priate at this stage to summarize the important results obtained
at McGill to highlight the outstanding areas of basic knowledge
required for the actual realization of FAE III.

In a FAE III, the fuel and the initiating chemical (catalyst)
are dispersed simultaneously to form a vapor cloud. The catalyst
then reacts with either the fuel or the oxygen in the atmosphere
to produce free radicals which then start the explosive oxidation
of the fuel-air mixture. It is evident that successful initiation
depends critically on the various characteristic times involved.
First, there is the mixing time between fuel and oxidizer "t_1",
second, between the catalyst and the fuel (or oxidizer) "t_2" if the
catalyst is not premixed with the fuel prior to dispersion, third,
the characteristic reaction time of the primary catalytic reaction
for a net production of free radicals "t_3" and fourth, the induc-
tion time of the secionary main oxidation reactions of the fuel-air
mixture initiated by the free radicals from the primary catalytic
reaction "t_4". If we consider diffusion losses of free radicals to
the cloud boundaries, then other characteristic times will also be
involved. The approach adopted by the McGill group is to investi-
gate first the simpler situations where more of the various charac-
teristic times are absent. Advancing progressively to more and more
complex situations, it is hoped that the necessary critical combi-
nation of all these characteristic times for successful initiation

can be obtained.

Eliminating first the mixing times t_1 and t_2, the direct initiation of a fuel-oxidizer mixture by free radicals was first studied. The free radicals were produced by photodissociation of a quiescent mixture and it was conclusively demonstrated that direct initiation of spherical detonation can be achieved non-thermally without shock waves if sufficient free radicals are introduced into the mixture. Of particular importance is the demonstration that apart from a critical maximum concentration of free radicals, a certain critical concentration gradient is also required for direct initiation. This study revealed the mechanism of Shock Wave Amplification by Coherent Energy Release or SWACER which is universal in all initiation processes.

Having demonstrated that free radicals when presented in a suficient number and distributed in an appropriate profile can lead to direct initiation, the next step was to investigate the mixing process. Here a simpler situation via the elimination of the reaction time for the primary catalytic reactions (i.e., t_3) was first studied. Free radicals already produced via combustion in the products was used to rapidly mix with a fresh unburned mixture to produce detonations. Again successful initiation has been demonstrated when a turbulent jet of combustion products (containing the free radicals) was injected into an unburned detonable mixture ($C_2H_2-O_2$ or C_2H_2-air). Of particular importance is the finding that large scale turbulence is required.

Finally, the combination of all three important time; mixing t_1, reaction time of the catalytic process t_2 and the induction time of the main explosive oxidation of the mixture t_3 were studied. The experiments consist of using propane (and butane) as fuel, oxygen (or air) as oxidizer and fluorine F_2 as the catalyst. The experiments consist of injecting a mixture of F_2 and O_2 (or air) and the fuel C_3H_8 (or butane) as two opposing turbulent jets into a spherical bomb. The combination of mixing times and flow parameters (turbulence intensity and scales) and the critical catalyst F_2 concentration for given fuel-oxidizer ratio are established for successful initiation of explosive oxidation.

The presentation at the meeting will summarize the main results obtained to date and the difficulties and major problem areas will be brought out.

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INITIATION COMBUSTION AND TRANSITION TO DETONATION
IN HOMOGENEOUS AND HETEROGENEOUS REACTIVE MIXTURES

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ABSTRACT

Third generation FAE devices require that localized enhanced re-
activity regions whose density is reasonably close to that of the main
cloud be produced in the cloud to initiate detonation after a single dis-
persing event. In this grant we are doing work to both theoretically and
experimentally verify the possibility of directly initiating detonation
by the proper distribution of an accelerator located in the midst of an
ordinary hydrocarbon-air mixture.

The theoretical portion of the program revolves about numerical
calculations using the CLOUD program which is a Lagrangian artificial vis-
cosity, single time step calculation for one-dimensional (planar, cylin-
drical or spherical geometry) nonsteady flow. Arrhenius reaction kinetics
of arbitrary order are used to deposit heat energy in each cell after time
t = 0 according to the equation

$$\frac{dQ}{dt} = \Delta E \frac{d\lambda}{dt} \quad ,$$

where the reaction coordinate changes according to

$$\frac{d\lambda}{dt} = A_o \frac{(1-\lambda)^n}{V^{n-1}} \exp(-E^*/RT) \quad .$$

At the present time the accelerator is modeled by increasing the pre-exponen-
tial factor in the reaction equation without changing the activation energy of
the reaction. Provision has been made for changing both the amount of acceler-
ator in the central region and the nature of the gradient region separating the
accelerator from the surroundings. This is important because it is well known
that a square wave accelerator concentration causing constant volume reaction
will not be capable of triggering the surroundings to detonation because the
temperatures behind the shock wave leading the accelerated reaction region will
just be too low to trigger the exothermic kinetics in the surrounding region.

Initially when we started to run CLOUD with this kinetic input we had a
great deal of difficulty because the kinetic expression allowed the rate of the
chemistry to become very high and this caused extremely small time steps be-
cause of the Courant criteria in the program. After we limited the time step
to get a reasonable value for the computation time, we then found that whenever

the gradient region became too steep an instability developed in which the radial dimensions of the cells did not agree with the actual cell volume calculated from mass conservation. This instability was greatly suppressed by including a predictor-corrector step to force closer agreement during each step of the calculation. The calculation is now stable because of the inclusion of this extra predictor-corrector step and an external limitation on the rate of heat release in any one element once the kinetic rate gets too large.

For the case where the accelerator distribution has a flat central core surrounded by a transition region, the maximum rate of heat release determined whether transition to detonation occurs. If the ratio of maximum rate of heat release to time for an acoustic signal to cross the enhanced region is too small, the pressure wave generated is not strong enough to start the reaction outside the enhanced region. If the ratio is just above a critical value, reaction occurs outside the enhanced region and a slow transition to CJ detonation takes place.

Experimentally we are just starting to look at flame propagation between two parallel plates in order to augment John Lee's study of acceleration of the flame by flame folding mechanisms over obstacles placed on the plates. We are using two plates about 0.7 m by 0.7 m placed above one another horizontally at spacings which can be varied from about 10 mm to 100 mm by using spacing rods at the corners. We blow a very large soap bubble of combustible mixture from the center of the bottom plate. When the bubble contacts the top plate it expands to form a cylindrical, combustible region. A spark is used to initiate the flame centrally. At the present time we are contemplating the use of schlieren and/or pressure records to determine effective flame velocity. We plan to put various obstacles on either the bottom or upper plate, either spiral, cylindrical, etc., to determine how flame folding and blockage causes acceleration of the flame. At the present time the program is just starting and there are no results to report as yet.

CHEMICAL INITIATION OF FAE CLOUDS
AFOSR Contract No. F49620-77-C-0097

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The objective of this work is the elimination of the second-
event system in FAE cloud detonation. There are two possibilities
for achieving this objective: Either the FAE cloud is generated
without ignition, as in the present state of the art, and then by
simultaneous dispersion of a chemical agent, or by the chemical
constitution of the fuel, the cloud is made to detonate spontane-
ously after an induction period; or fuel dispersion and combustion
occur simultaneously at such high rate that an effective blast-
generating piston force is maintained throughout the process of
cloud generation and combustion. The first possibility has received
only cursory attention in the present studies, because its implemen-
tation as a single-event FAE system appears to be rather difficult.
The second possibility seems to be feasible and much less complicated.
The basic principle is already known from the blast augmentation that
occurs with underoxidized explosives in air by combustion of the fuel
residue of the detonating charge; that is, the combustible detonation
products mix and burn with air at such high rates that the combustion
energy makes an effective contribution to the blast wave. A FAE cloud
would produce a blast wave analogously if the fuel were made to dis-
perse and burn at such high rate that the cloud/air interface moves at
a velocity comparable to the particle velocity in a fuel/air detonation
wave. This leads to the concept of a FAE system in which the primary
explosive charge drives a fluorine agent such as CTF (ClF_3) or BTF
(BrF_3) into a surround of hydrocarbon fuel such as Diesel oil, which
accordingly would disperse and burn like a detonating high-explosive.
In a cylindrical configuration the core of the system would be a rod of
a solid high-explosive surrounded by a steel jacket in which the fluorine
agent is incased. Detonation of the high-explosive would shatter the
jacket and inject the agent into the surrounding hydrocarbon fuel. The
resulting rapid dispersal of the fuel in the ambient atmosphere would
sustain a blast wave depending on the mass flow generated by the process
of dispersal and combustion.

Exploratory open-air tests have been performed in the laboratory
by pneumatically driving small slugs of liquid BTF and CTF into
Diesel oil. For practical reasons the fuel quantity was limited to
volumes of less than one milliliter, which is the order of 10^{-6} to
10^{-7} times smaller than the fuel quantity in full-scale FAE systems.
At this small scale, the blast generation by fuel dispersal and com-
bustion requires ejection of atomized fuel particles into the ambient-
air to radial distances of the order of 10 cm within less than about
300 microseconds. The ejection momentum that was achievable in these

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experiments fell short of this requirement but nevertheless did yield a significant augmentation of the blast by fuel/air combustion. When the ambient atmosphere was oxygen instead of air and the required ejection distance was accordingly reduced to the order of 5 cm, the blast effect was increased to the limit of safe laboratory experimentation. These data lead to the expectation that a FAE effect utilizing most or all of the combustion energy of the fuel can be demonstrated by increasing the test scale and using an explosive charge for driving the agent into the fuel.

The schematics of the larger-scale FAE tests that are being conducted under the present program are illustrated in Figure 1. An annular stainless-steel vessel containing liquid CTF is surrounded at its periphery by Diesel oil and contains a solid high-explosive charge in its core. Confinement for the period between detonation of the charge and ejection of the fluids is provided by sandwiching the assembly between massive steel blocks. The CTF/oil reaction plus the primary detonation drives the fuel into the surrounding atmosphere, forming a cloud of atomized oil and generating a strong primary air shock. The oxygen carried into the cloud by air entrainment reacts instantly with the fuel and increases the cloud momentum, thus generating the FAE effect.

Initial tests will be performed with 350 cc (300 gram) of Diesel oil and 35 cc (63 g) of CTF. The overall diameter of the device is about 7 inches and the space between the steel blocks is about 5/8 inch wide. The CTF annulus has an outer diameter of 2 inches and an inner diameter of 1/2 inch with corrections for the wall thickness. The volume of the explosive charge is approximately 5 cc which corresponds to a weight of about 8 grams. These data are based on the following estimates:

If the pv-work generated by the explosive is taken to be of the order 1 kcal per gram and that of the CTF/oil reaction to be no less than 1/2 of the heat release of 168.5 kcal per mole (1.82 kcal/g CTF), one obtains from 8 gram explosive and 63 gram CTF a total pv-work of no less than 65 kcal = 6.5×10^6 foot-poundals for driving 300 g oil minus 19 g consumed in the reaction, or 0.62 pounds. The oil would thus be injected into the ambient atmosphere at a velocity of not less than $\sqrt{2 \times 6.5 \times 10^6/.62}$ = 4,600 ft/sec = 1400 m/sec and would produce a shock wave in the air which may be of the order of 1700 m/sec, or about Mach 5. The subsequent fuel dispersion and combustion would, to a considerable distance from the explosion center, proceed via Taylor instability, and as this effect subsides it would be continued by turbulence which is supported by the randomly distributed combustion centers in the cloud.

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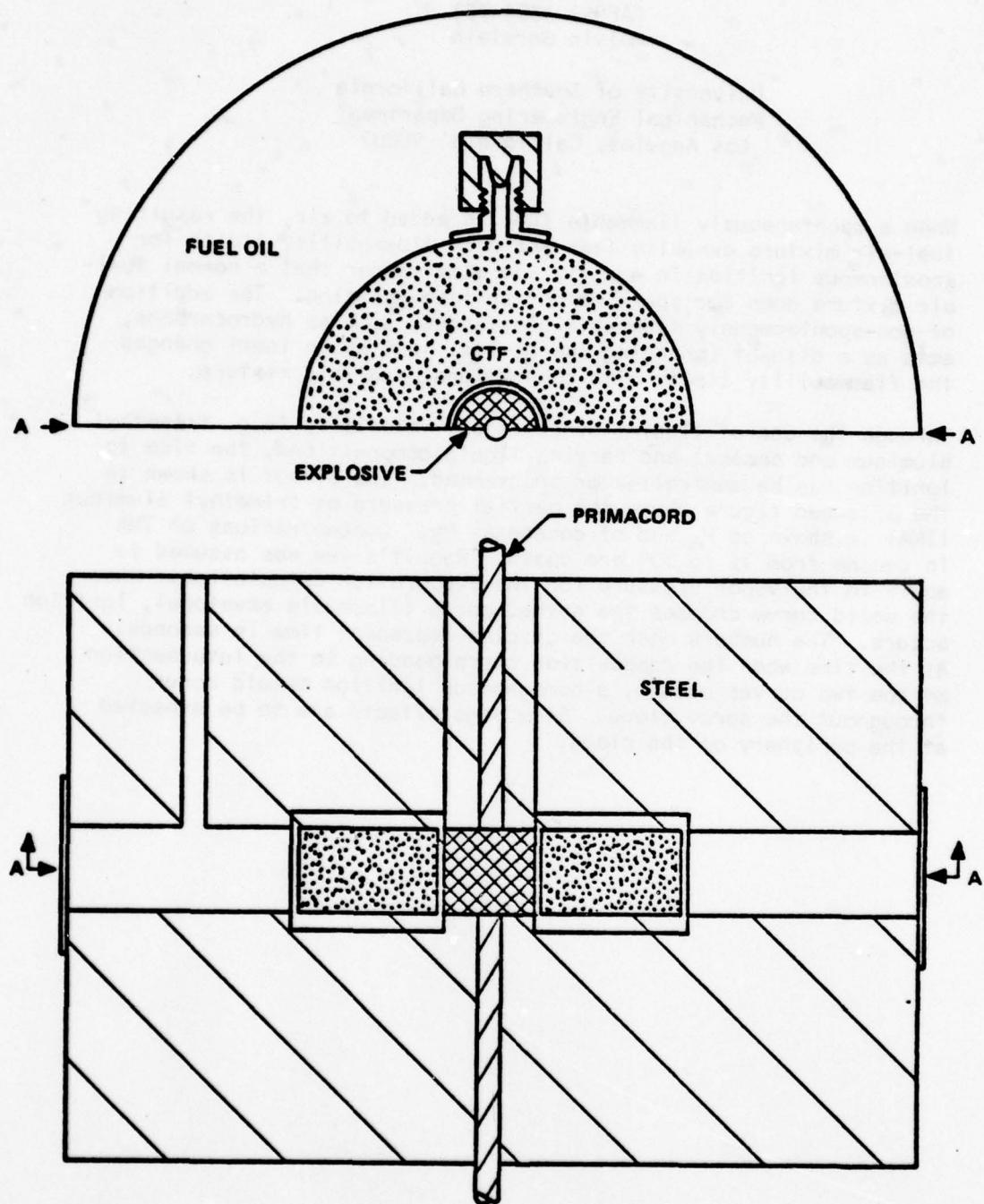
Figure 1. Concept of Test Configuration (No Scale).

USE OF SPONTANEOUSLY FLAMMABLE ADDITIVES TO
INITIATE FUEL-AIR EXPLOSIONS
(AFOSR 3354-77)
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When a spontaneously flammable fuel is added to air, the resulting fuel-air mixture exhibits lean and rich flammability limits for spontaneous ignition in exactly the same manner that a normal fuel-air mixture does for spark or hot surface ignition. The addition of non-spontaneously flammable substances, such as hydrocarbons, acts as a diluent (changing the limits) just as an inert changes the flammability limits of a conventional fuel-air mixture.

Through the use of liquids of different volatility (e.g. trimethyl aluminum and decane) and varying liquid compositions, the time to ignition can be controlled or programmed. The effect is shown in the attached figure where the partial pressure of trimethyl aluminum (TMA) is shown as P_A and of decane as P_B. Concentrations of TMA in decane from 1% to 50% are shown. Raoult's law was assumed to apply to the vapor pressure for the evaporation calculation. When the solid curve crosses the dashed curve (flammable envelope), ignition occurs. The numbers near the circles represent time in seconds. At the time when the composition corresponding to the intersection of the two curves occurs, a homogeneous ignition should occur throughout the spray cloud. Some edge effects are to be expected at the periphery of the cloud.

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RADIATIVE AUGMENTATION OF COMBUSTION

Contract NAS8-xxxxxxx

A. S. Gordon and C. S. Stevens
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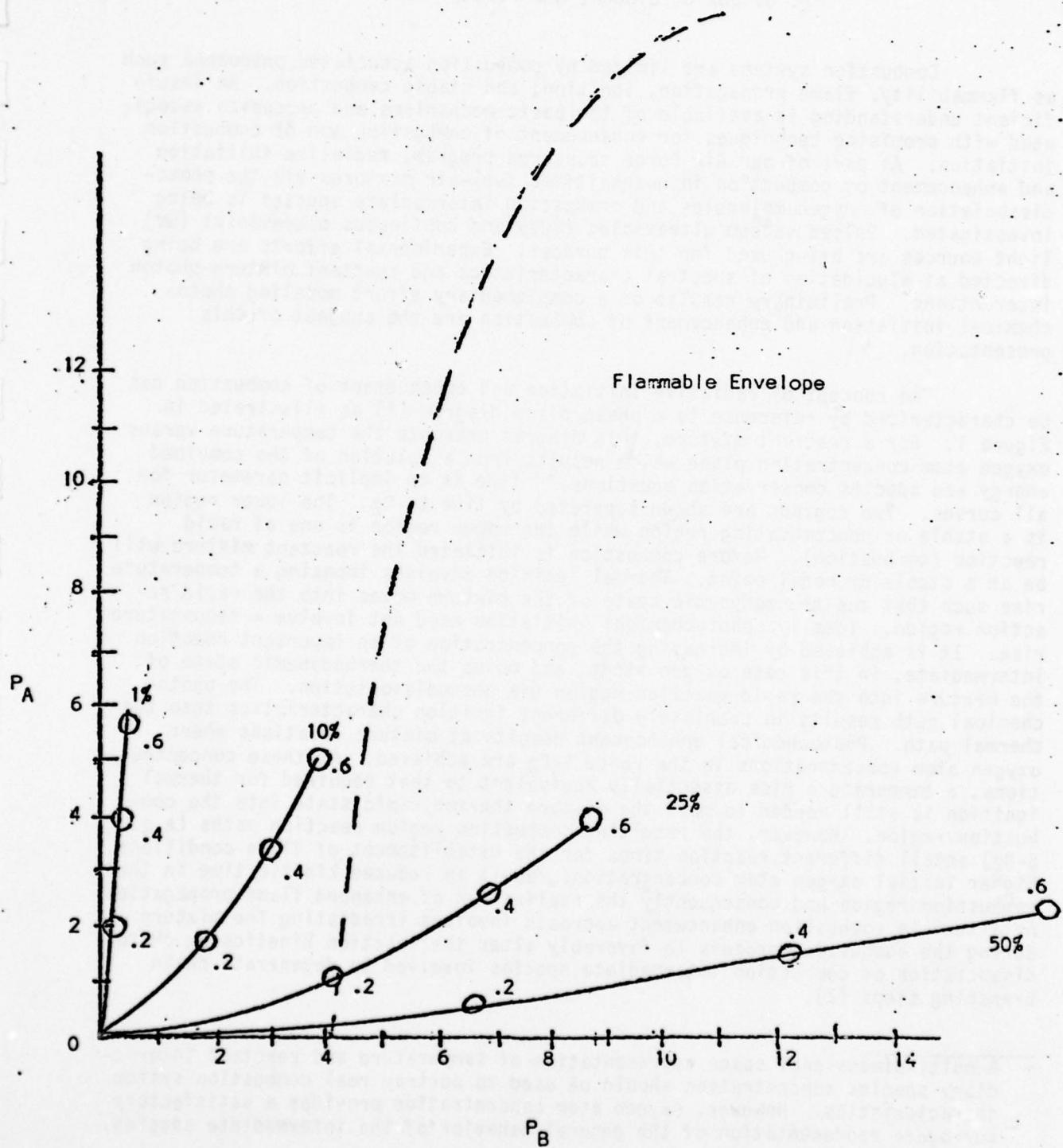
Ignition curves for TMA-Decane mixtures.

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RADIATIVE AUGMENTATION OF COMBUSTION
CONTRACT F49620-77-C-0085

A. E. Cerkanowicz and J. G. Stevens
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Combustion systems are limited by combustion associated phenomena such as flammability, flame propagation, ignition, and stable combustion. An insufficient understanding is available of the basic mechanisms and processes associated with promising techniques for enhancement of combustion and of combustion initiation. As part of our Air Force sponsored program, radiative initiation and enhancement of combustion in unsensitized fuel-air mixtures via the photodissociation of oxygen molecules and combustion intermediate species is being investigated. Pulsed vacuum ultraviolet (VUV) and continuous ultraviolet (UV) light sources are being used for this purpose. Experimental efforts are being directed at elucidation of spectral characteristics and reactant mixture-photon interactions. Preliminary results of a complementary effort modeling photochemical initiation and enhancement of combustion are the subject of this presentation.

The concept of radiative initiation and enhancement of combustion can be characterized by reference to a phase plane diagram (1) as illustrated in Figure 1. For a reactant mixture, this diagram presents the temperature versus oxygen atom concentration plane which results from a solution of the combined energy and species conservation equations.[+] Time is an implicit parameter for all curves. Two regions are shown separated by line C_1-C_2. The lower region is a stable or noncombusting region while the upper region is one of rapid reaction (combustion). Before combustion is initiated the reactant mixture will be at a stable or nodal point. Thermal ignition involves imposing a temperature rise such that the thermodynamic state of the mixture moves into the rapid reaction region. Ideally, photochemical initiation need not involve a temperature rise. It is achieved by increasing the concentration of an important reaction intermediate, in this case oxygen atoms, and moves the thermodynamic state of the mixture into the rapid reaction region via photodissociation. The photochemical path results in completely different ignition characteristics than the thermal path. Photochemical enhancement results at mixture locations where oxygen atom concentrations in the range S-C_2 are achieved. At these concentrations, a temperature rise essentially equivalent to that required for thermal ignition is still needed to move the mixture thermodynamic state into the combustion region. However, the resulting combustion region reaction paths (e.g. S-N_2) entail different reaction times for the establishment of flame conditions. Higher initial oxygen atom concentrations result in reduced kinetic time in the combustion region and consequently the realization of enhanced flame propagation. An alternate combustion enhancement approach involves irradiating the mixture during the combustion process to favorably alter the reaction kinetics by photodissociation of combustion intermediate species involved in degenerate chain branching steps (2).

[+] A multi-dimensional space representation of temperature and reactant intermediary species concentration should be used to portray real combustion system characteristics. However, oxygen atom concentration provides a satisfactory surrogate representation of the general behavior of the intermediate species.

A comprehensive model of radiative initiation and enhancement of hydrogen-oxygen-nitrogen mixtures is being developed. The model includes the effect of light source characteristics; photodissociation of light absorbing species, reactant mixture kinetics, including electronically excited state species; and adiabatic temperature rise due to reaction heat release. The species considered in the radiative initiation and enhancement model for the $H_2-O_2-N_2$ system are listed in Table 1. A literature review was undertaken and best values for the rate constants in the form $AT^{-B} \exp(-C/T)$ for reactions involving these species were obtained. The current version of the model considers approximately ninety such reactions. The minimal set required and a sensitivity analysis of the rate data for those dominant reactions is under investigation.

Radiant absorption by reactant and combustion-intermediate species is considered to follow a Beer-Lambert Law. The dissociation products formed, which may include excited states, are dependent on the energy of the photon absorbed. The photodissociation reactions which can occur are also listed in Table 1.

For a given absorbing species dissociating to specified products, the unimolecular photochemical reaction rate constant is given by the following equation.

$$k(x,t) = \int_0^\infty I(x,t,\lambda)T(\lambda)\phi(\lambda)[\lambda/hc]\sigma(\lambda)\exp\left[-\sum_{i=1}^N \sigma_i(\lambda)\int_0^x n_i(x,t)dx\right]d\lambda$$

where: t = time
x = distance from light source window
λ = wavelength
n_i = concentration of light absorbing species
σ_i = absorption cross-section of light absorbing species
ϕ = quantum yield of dissociation
T = window transmission
I = source irradiance

Quite general light source characteristics can be considered in the specification of the source irradiance. Intensity is considered to be dependent on wavelength, time, input energy, and optical arrangement (i.e. parallel beam, focused beam, point source). As well, the transmission characteristics of window material such as quartz or sapphire can be incorporated by specification of window transmission. Absorption coefficients for all light absorbing species are tabulated, and the treatment of molecular oxygen absorption in the Schumann-Runge bands follows that given by G. Kockarts (3). In the current implementation of the model, all absorbing species are reckoned to dissociate with the rate constant calculated from the cited equation, but the attenuation of light intensity by the mixture is taken to be due solely to O_2. This assumption is reasonable, even in wavelength regions in which O_2 does not absorb strongly, due to the low column density of the other absorbers during the irradiation period.

The final model equations are thus the collection of rates of change in species concentrations due to reaction and photodissociation, together with an adiabatic heat balance. Future plans call for the inclusion of diffusion, heat loss, and wall recombination effects as well as consideration of methane fueled systems. The resulting nonlinear system of differential equations was solved to high-order accuracy using the stiffly stable multistep method of Gear (4). An equation-writer code received from Los Alamos Scientific Laboratory was modified to aid in the generation of the code required to describe the chemical kinetic effects of a large number of reactions on the individual species balance equations (5). The program also produces code to calculate the Jacobian of the system.

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Figure 2 illustrates model predictions for the irradiation of a 298 K, 40 kPa, hydrogen-oxygen mixture. Each curve represents a photochemical path (time implicit) in the phase plane for a given radiant intensity. The radiant pulse was assumed to be a critically damped discharge with a time to peak intensity of 20μs. For low radiant intensities (50, 75, 80) the radiant pulse generates oxygen atoms and some temperature rise, but the final tendency of the mixture is to return to the initial conditions that existed before irradiation. This fact is indicated by the flattening out of the temperature profile, and the failure to achieve combustion within a characteristic heat loss period because no heat loss is currently accounted for in the model. At higher radiant intensities (85, 90, 100), the irradiated mixture has entered the unstable zone and the tendency to return to the initial conditions is overcome. All of these high intensity conditions eventually result in rapid burning (combustion). These results indicate that a critical radiant intensity exists below which ignition is not achieved, in agreement with earlier experimental results (1). The nature and character of the curves are compatible with the combustion system behavior indicated by a general phase plane analysis.

The inclusion of electronically excited state species favorably alters the kinetics resulting in improved combustion behavior. Both intensity and time to achieve rapid reactions are reduced by the presence of excited state species. When the model is altered so that only ground states are reckoned to be produced by photodissociation, thus effectively eliminating all excited state kinetics, the radiant energy needed to achieve combustion is approximately twice that required with the inclusion of excited states. Thus, it is clear that excited state species and their reactions must be included in the modeling of photochemical initiation and enhancement of combustion. Optimization of the spectral distribution of light source radiation is also shown to be an important consideration. Radiation in the spectral region from 145-165 nm is critical for reaction initiation while initiation kernal growth is influenced by 145-180 nm radiation. Enhancement of flame propagation is brought about by radiant energy in the 165-200 nm range. The existence of an optimum pulse period for effective coupling of the radiant input energy to the kinetic reactions for combustion initiation is also indicated.

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FIGURE 1
PHASE PLANE DIAGRAM FOR AN
ADIABATIC HYDROGEN-OXYGEN COMBUSTION SYSTEM

TABLE 1
HYDROGEN-OXYGEN PHOTOCHEMICAL SYSTEM
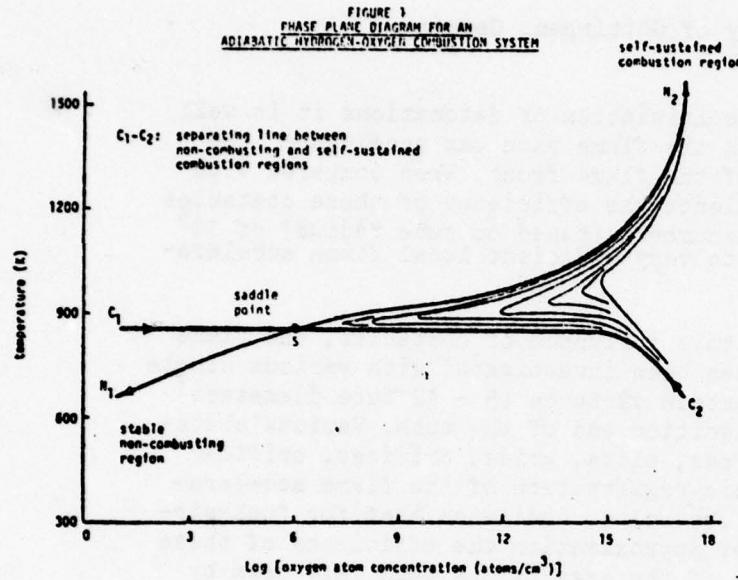
REACTANT SPECIES

$O(^1D)$	O_2	OH
O	O_3	H_2O
$O_2(^1\Sigma_g^+)$	H	HO_2
$O_2(^1\Delta_g)$	H_2	H_2O_2

PHOTODISSOCIATION REACTIONS

$O_2 + h\nu\ (\lambda < 245) \rightarrow O + O$

$O_2 + h\nu\ (\lambda < 175) \rightarrow O + O(^1D)$

$O_3 + h\nu\ (\lambda < 1140) \rightarrow O_2 + O$

$O_3 + h\nu\ (\lambda < 310) \rightarrow O_2(^1\Delta_g) + O(^1D)$

$O_3 + h\nu\ (\lambda < 260) \rightarrow O_2(^1\Sigma_g^+) + O(^1D)$

$H_2O + h\nu\ (\lambda < 242) \rightarrow OH + H$

$HO_2 + h\nu\ (\lambda < 456) \rightarrow OH + O$

$H_2O_2 + h\nu\ (\lambda < 365) \rightarrow OH + OH$
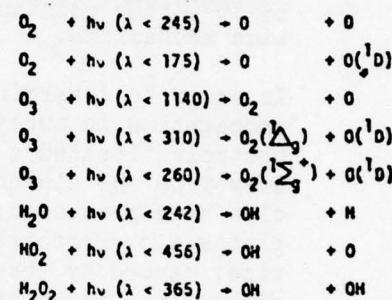
FIGURE 2
REACTANT MIXTURE PHASE PLANE PATHS
DURING PULSED VACUUM ULTRAVIOLET IRRADIATION

35
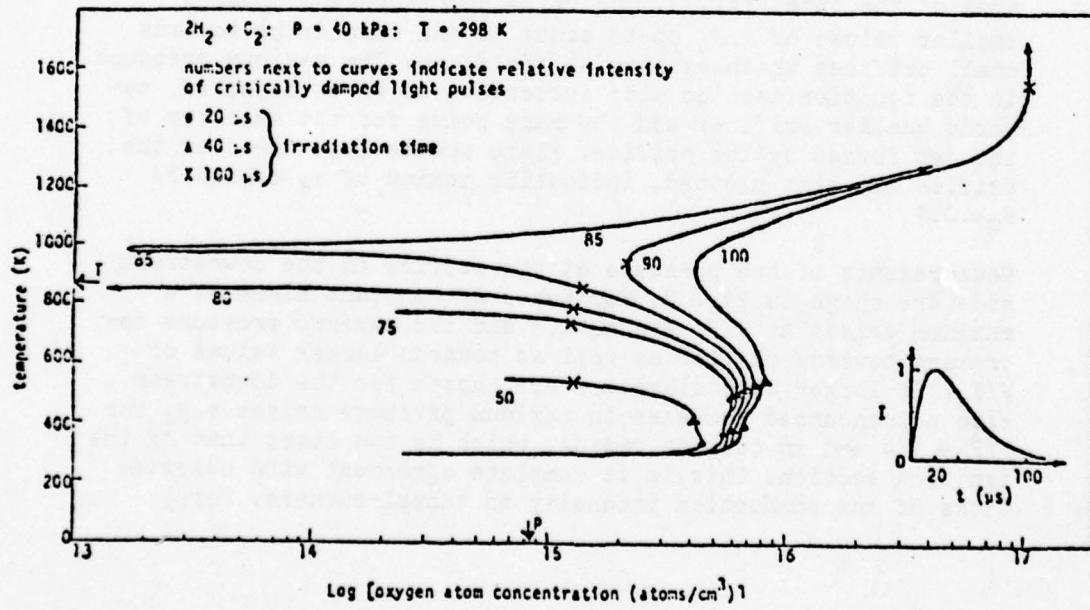
ON THE INFLUENCE OF A SINGLE ORIFICE ON THE PROPAGATION OF FUEL-AIR-FLAMES
Grant AFOSR-78-3587

Professors W Jost and H Wagner, D. Pangritz

University of Göttingen, Germany

From experiments on the initiation of detonations it is well known that obstacles in the flame path can accelerate the propagation velocity of the flame front. When compared with normal tube flow turbulence the efficiency of these obstacles corresponds to Reynoldsnumbers (based on tube radius) of 10^5 to 10^6, thus pointing to very efficient local flame acceleration mechanisms.

In order to determine this influence of obstacles, the flame propagation in tubes has been investigated with various single obstacles located a certain distance (5 - 12 tube diameters) away from the closed ignition end of the tube. Various obstacles have been used: rods, slits, grids, orifices, orifice plates a.o. Photographic registration of the flame acceleration, caused by these obstacles, indicates that for fuel-air-flames in a first order approximation the efficiency of these obstacles was the same if the area of the tube left open by the obstacles (F) remained the same. Most of the experiments reported here have therefore been performed with circular orifices. A first indication of the efficiency of these obstacles can be obtained from smear camera pictures if the ratio (α) of the flame speed behind (v_2) and ahead of the obstacle v_1 ($\alpha = v_2/v_1$) is plotted as a function of F/F_O where F_O is the area of the tube (Fig.1). The value of α increases towards smaller values of F/F_O up to about 50 and than drops towards small orifices which extinguish the flame. The maximum pressure in the ignition section also increases, as to be expected, towards smaller orifices and the same holds for the velocity of the jet formed by the orifice. Flame speeds (v_1) ahead of the orifice are also plotted, indicating maxima of v_2 around $F/F_O \approx 0.1$.

Measurements of the pressure at the orifice on the downstream side are shown in Fig. 2. For tubes of constant diameter a maximum arises at F/F_O around 0.3 and the maximum pressure decreases towards smaller as well as towards larger values of F/F_O. If larger tube diameters are chosen for the downstream side a pronounced increase in maximum pressure arises e.g. for $F/F_O = 1/4$ and an outside radius, which is two times that of the ignition section. This is in complete agreement with observations of the combustion intensity in tunnel-burners. For

larger outside tube diameters the measured p values decrease. This is due to less confinement and does not mean that within the main combustion zone the combustion intensity is much less than in the optimum case.

Various fuel-air-mixtures have been checked for the maximum pressure which could be achieved after one obstacle (orifice, orifice plate, slit) for optimum F/F_o and optimum ratio of downstream to upstream (mostly 2:1) tube radius. These data correlate quite well with the laminar flame speed Λ of the mixtures investigated (situation becomes different for oxygen enriched air). It should not be overlooked that they have been obtained in a rather confined situation and that the other measured date lay below that curve (Fig. 3).

For the transition of these flames through orifices three mechanisms can be obersved:

(1) If the orifice is very small ($2\,r \leqslant 5$ mm, somewhat depending on the shape of the orifice and the fuel) combustion does not proceed through the orifice.

(2) If the orifice is large, the flame just passes through the orifice as a flame tongue, of course feeling the increased turbulence level caused by the large orifice.

(3) For medium size orifices, the flame is extinguished and reignites some distance X away from the orifice. This distance can be observed on the smear camera photographs and on the movie films. How this distance X depends on the experimental conditions for various values of F/F_o is shown in Fig. 4. With decreasing F/F_o the maximum pressure in the ignition section and the velocity of the jet of unburned gas flowing out of the ignition section increases. Mass flux and momentum flux decrease (Fig. 1). This jet entrains gas and generates turbulence. For a 40 mm diameter ignition tube and a 200 mm downstream tube, the jet is a free jet as in an unconfined system. For a confined jet (40/40) the ignition distance becomes shorter. When the flame reaches the orifice, burned gas (and/or flame kernels) follow the jet of unburned gas and rapidly entrain unburned highly turbulent gas (eddy diffusion coefficient around 500 cm^2/sec). In the movies one can observe that, starting at distance X from the orifice, a flame ball, carried downstream in the jet flow, grows with very high speed in any direction ($dr/dt \approx$ 50 - 100 m/sec.

By the rapid mixing of the hot, reacted, radical containing gas with unburned mixture, zones of high reactivity are generated transitorily, which can, if sufficient time is available, (in contrast to case 1) undergo selfignition. Flames can propagate in these mixtures locally with very high speed (high turbulence, increased temperature).A semi-quantitative description can be given for these reacted-unreacted-gas mixing controlled processes.

If the air is oxygen enriched, the processes become more violent and detonation can be initiated. Mounting more than one orifice plate at proper distances also lead to high pressures and effective propagation velocities, for CH_4-air even faster than those obtained by Wheeler.
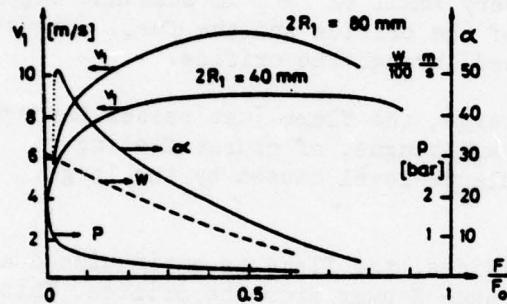

Fig.1 Influence of orifice; C_2H_4 -air in tube of $2R_1$
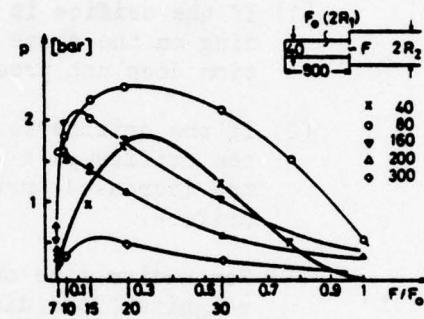

Fig. 2 Maximum pressures for C_2H_2 - air
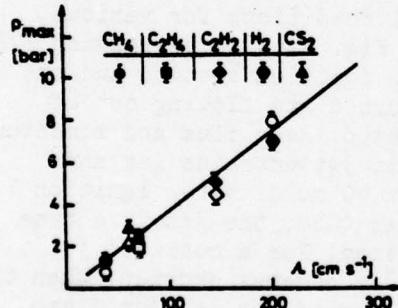
Fig. 3 Maximum peak pressures
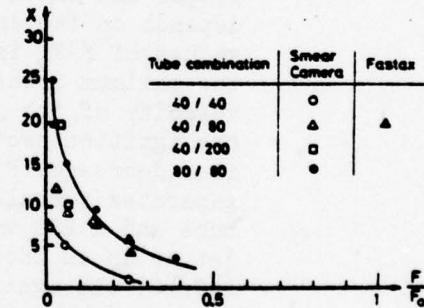
Fig. 4 Ignition distances X

IGNITION, COMBUSTION, DETONATION and QUENCHING
of REACTIVE GAS MIXTURES
(AFOSR 78-3604)
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Experiments to determine the acceleration of flames in unconfined fuel-air mixtures have been discontinued temporarily because of limitations in our research facility. We have received several complaints on the 'shock' waves felt by residents located several miles away from our laboratory. On the other hand pressure measurements in the near-field of these explosions did not indicate the presence of shock waves. To avoid this environmental problem we have started a series of experiments in closed tubes to determine the factors which tend to reduce the detonation induction distances in fuel-air mixtures. In previous experiments we have established very clearly that flames, propagating into explosive gas mixtures which are cooled to very low temperatures, form detonation waves after extremely short distances of travel. However, the mechanism responsible for the large reductions of the induction distances of these mixtures with decreasing temperature is not well understood. Since the normal flame speeds of all combustible gas mixtures are always lowered when the temperature of the unburned gas is reduced, the reductions of the induction distances must be caused by some gas dynamic effects. One reason might be the fact that the speed of sound in the cold gas mixture is lower than that in the same mixture at room temperature. Thus the initial compression wavelets produced by the expanding burnt gases may not travel very far before they coalesce to form a shock wave of sufficient strength to ignite the combustible gas mixture ahead of the flame at a rather close distance from the ignitor. However, it must be remembered that the speed of sound in a gas is proportional only to the square root of the gas temperature whereas according to our measurements the normal rate of flame propagation was found to be directly proportional to the temperature of the unburned gas. In our previous experiments all induction distances which were measured at different initial temperatures were determined at atmospheric pressure. Thus the density of the unburned gas was inversely proportional to its temperature. Because of this fact it was assumed that the increase of the unburned gas density is responsible for the observed decrease of the induction distances. However, a series of experiments carried

out with fuel-air mixtures in which the nitrogen was replaced by both high molecular mass (e.g. argon) and low molecular mass (e.g. helium) gases revealed that the effect of the initial gas density on the induction distance is not conclusive. It appears that the chemical kinetics of the combustion process is altered when different inert gases are used in the mixtures. In principle any combustion of a premixed explosive gas mixture can occur either at constant pressure (Bunsen flame), or at constant volume (weak detonation), or somewhere between these extremes. Although our measurements revealed that the pressure behind the flame front rises very rapidly to the value of the stable detonation wave when the initial gas temperature of the combustible gas mixture is low whereas it remains practically unchanged over a long distance from the ignitor when the initial gas temperature is raised to room temperature or above, it cannot be concluded that the induction distance is a simple function of the gas density. To obtain a quantitative relationship between the state of the unburned gas and the length of the induction distance a series of experiments is under way to determine the effects of initial temperature and pressure as well as the effect of inert gas admixtures of different molecular mass. Preliminary measurements of the induction distances in H_2 + 1/2 O_2 + 1/2 A and H_2 + 1/2 O_2 + 1/2 He mixtures have shown that at an initial pressure of 1 atm the induction distance in the mixture containing argon is much shorter than in the mixture containing helium. However, at an initial pressure of 3 atmospheres there is practically no difference in the induction distances of these two mixtures.

INSTABILITY MECHANISMS

RELATED TO DETONATION WAVE STRUCTURE,

STABILITY AND INITIATION REQUIREMENTS

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ABSTRACT

This research on instability mechanisms involved in the
mutual influence among sound, entropy, and vorticity modes in
chemically reacting subsonic and supersonic flows will aid in
the design and development of practical combustors for advanced
air-breathing and hybrid engines, for MHD generators and chemical
lasers. Further, it will also provide the fundamental informa-
tion needed to solve many practical problems related to noise
pollution and unconfined explosions.

One basic mechanism that plays an important role in trigger-
ing and sustaining instabilities in chemically reacting flows,
such as that related to combustion instabilities, detonation
wave structure, turbulence spectra in reacting flows, etc., is
due to the coupling between chemical kinetics and gas dynamics.
Such coupling could lead to wave interactions which would
sustain the instability structures observed in a number of
problems[1].

During the initial phase of the development of the
instabilities, the amplitudes of the waves involved are usually
small and the wave-kinetic interactions can be treated in a
linear acoustic analysis (despite non-linear chemical kinetics
through temperature and concentration dependence). Considerable
insight on such acoustic-kinetic interactions has been obtained
in several theoretical studies [1-6]. Furhermore, predictions in
the quasi-steady regime, when the ratio Ω of the characteristic
chemical time to the acoustic period is large, are found to
agree well with the experimental results in H_2-Cl_2 systems[7,8].

During the later phase of the development of the instabili-
ties, the wave amplitudes become large and the accompanying non-
linear effects may become important. Such non-linear wave-
kinetic interactions have been identified by examining the
propagation of weak shocks in exothermic reacting mixtures.

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A non-linear wave equation that takes into account the non-equilibrium chemical effects has been developed for high-frequency waves. The equation is numerically integrated to predict the amplification rate under different reaction conditions.

For relatively low activation energies, the numerical solutions show that the wave-kinetic interactions are not sufficient to sustain weak shocks including dissipative losses. The rate of decay of the shock waves increases at high shock strengths. Moreover, higher thermicities tend to lead to attenuation rather than amplification. Experimental results at shock strengths up to Mach 1.2 in hydrogen-chlorine-argon mixtures have confirmed these predictions.

For detonable mixtures with high activation energies, dramatic amplification rates have been predicted. These rates are enhanced with increasing shock strength and pulse duration. Furthermore, a minimum pulse duration is required for shock of a given initial strength to develop into a stronger shock. These results seem to indicate that threshold values for both shock strength and pulse duration exist for direct initiation of explosions.

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Ignition of a Liquid Fuel Under High Intensity Radiation

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Laser technology has been rapidly advancing in the last two decades. Power outputs of modern lasers have increased significantly and these lasers can be used as tactical weapons. A high power laser weapon can ignite aircraft fuel through fuel tank penetration and can cause fire or explosion of the aircraft. The objective of this study is to obtain a fundamental understanding of physical and chemical mechanisms of the ignition of liquid fuels under high intensity radiation, thus enabling future improvements in aircraft survivability from fire and explosion threats.

Since the radiative ignition of flammable liquids is hardly know, an experimental study is being conducted to clarify the key mechanisms of ignition. The following experiments were conducted using a CO_2 laser and n-decane as the flammable liquid. The first was to take high speed photographs of the motion of the decane surface after its exposure to the incident laser beam and of the onset of ignition in the gas phase. Results would reveal the behavior of the decane surface during the heating period and the location of the first ignition and subsequent flame spread. The second was to find the effects of incident angle of the laser beam with respect to the decane surface on ignition delay time. The third was to measure the extinction coefficient of liquid decane at laser wavelengths to find how deep the laser beam penetrated into the decane.

High speed motion pictures show clearly the motion of the decane surface prior to ignition. When the laser beam irradiated the decane surface, a small amount of splash of decane was observed followed by small waves moving radially outward. This behavior appears similar to that seen when a stone is thrown into a pond. Boiling of the decane was vigorous accompanied with bursting sounds similar to that heard when water droplets would fall onto a high temperature plate. The onset of ignition was observed in the gas phase far from the decane surface. On reducing the incident angle of the laser beam to the decane surface, the onset of ignition occurred further away from the plume centerline, i.e., toward the edge of the plume. Rapid flame spread along the plume of the decane vapor was observed immediately after ignition. Color photographs showed that bright yellow color of a small rod shape at the location where the incident laser beam interacted with the plume of the decane vapor. This was much brighter color than the rest of flame and it remained until the laser beam was turned off. From this observation, it is considered that the absorption of the laser beam by the decane vapor is the key heating process of the gas phase prior to ignition. This was confirmed by the ignition of vapor from decane heated by an electrical hot plate by passing the laser beam through the vapor parallel to but above the liquid decane surface. Therefore, the ignition mechanism of decane by high intensity radiation is the absorption of the incident radiant energy by its vapor plume.

The relationship between the ignition delay time and the incident flux were studied with various incident angles of the laser beam at 30°, 45°, 60°, 75° and 90°. Below 2500 W/cm^2, ignition delay time increases significantly with a decrease in flux. There is a peculiar trend where ignition delay time tends to

increase slightly with incident radiant flux in the range of high flux. This was observed that the minimum incident radiant flux for ignition, I_{min}, increases with a decrease in the incident angle. At $\theta = 75°$ and $90°$, $I_{min} \simeq 1000$ W/cm^2, but at $\theta = 60°$, $I_{min} \simeq 1400$ W/cm^2, at $\theta = 45°$, $I_{min} \simeq 1800$ W/cm^2 and at $\theta = 30°$, $I_{min} \simeq 2000$ W/cm^2. The relationships between the ignition delay time and the incident flux do not differ from each other significantly at $\theta = 60°$, $75°$ and $90°$ except near the ignition boundary. However, the relationships at $\theta = 30°$ and $45°$ differ significantly from other angles. Ignition delay time becomes longer over a wide range of the incident radiant flux.

To obtain the extinction coefficient of liquid decane, linear absorbance was measured from wave number 1100 to 800 cm^{-1} by a Perkin-Elmer Model 180 Infrared Photometer using a variable length cell. It was found that the absorbance of the decane was sensitive to the wave number near the CO_2 laser lines.

Therefore, the bulk extinction coefficient of decane was calculated from the spectra of the fine rotational structure of the CO_2 laser and the linear absorbance. Since the rotational line of the laser is much narrower than absorption bands of decane, the laser line was considered to be delta function in the integration along the wave number. The calculated extinction coefficient of decane is 17 cm^{-1}. This is much smaller than for many solids. For example, about 90 cm^{-1} of solid polystyrene. Therefore, the laser beam penetrates into decane and heats a larger volume than polystyrene. This is one of the reasons why decane requires higher incident flux for ignition and its ignition delay time is longer than polystyrene.

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DETONATION PHENOMENA IN NONIDEAL CONDENSED EXPLOSIVES

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ABSTRACT

Observed nonideal detonation phenomena are described along with
some of their probable effects on explosives systems and the loads
to which such systems are applied, i.e. Air Force munitions.

There are several reasons to be interested in condensed nonideal
explosives. One is their value in studying detonation itself.
Another is potential usefulness as a class of materials, with
either industrial or military applications. Our present concern
is of course the last, and the approach is now largely the exper-
imental determination of detonation and related parameters, gather-
ing data for calculational and theoretical development. Operational
and other characteristics also receive attention because the util-
ization potential is thought to be high.

A convenience one might use to define ideality in condensed explo-
sives is time dependence. If the detonation chemical reaction is
not almost instantaneous or infinite-rate with respect to the size,
geometry, time scale of the system, the material could be considered
nonideal. It may be inferred from this definition that any explo-
sive may be or seem to be either ideal or nonideal.

Nevertheless, the definition is useful because, as will be shown,
ideality of performance can be and has been modified by varying
reaction time of intermolecularly-reacting systems, prificipally
by varying transport through control of particle sizes or the
equivalent, intimacy of mix.

For military bulk-use condensed explosives, the principal charac-
teristics are performance, availability/producibility, tactical
and strategic features, cost, and safety. These are often permuted.

Performance, for main-charge purposes, can be classified into three
kinds: fragmentation (brisance); penetration and controlled metal
motion; and blast (air, underwater, earth-moving).

High detonation pressure has been observed to yield many small frag-
ments from smooth metal cases. The total energy Q is not so im-
portant , while the effect of detonation velocity is partly as it
is related to pressure, which is partially functional with the

square of detonation velocity,

$$P = \rho D^2/\gamma + 1$$

The effect of gamma, one of the CJ parameters which is not measured, on pressure is seen in the equation. The effect of detonation temperature, another unmeasured parameter, on fragmentation is not clear but is probably small; perhaps high T serves to accelerate fragments with energy delayed by conversion from thermal to translational.

It may be possible to have too high a pressure, if energy is limited and too much is used in compression/shock heating of the metal. That energy is then internal instead of kinetic, and a result might be very small easily-slowed fragments.

Avoiding compression heating and high internal shock pressures may be more important in controlled metal motion, e.g. in shaped charges and other forming and propulsion applications.

Ways to get relatively shockless but energetic propulsion are not entirely developed, and the tailoring of explosives to the task has hardly begun. This is one region in which nonideals should be able to serve well, by reducing peak pressure while keeping the P-V curve high during early time folllwing CJ.

Nonideals are also well suited to blast, since airblast, underwater bubbles, and earth moving are more responsive to total energy Q of the explosive than to the rate of detonation reaction. Nonideals can have higher potential energy density Q_v, not being as limited by the need to have all the energy built into the molecule as is generally the case for ideals. Instead, one can choose highly exothermic and dense partners, giving up ultrafast reaction kinetics in favor of energy density. Examples are given.

Performance of composites is a function not only of the chemistry of reaction but also of physical or mechanical factors, the most effective of which is distance between reactants, e.g. as measured by particle sizes. Effects of particle size on performance of composites are indicated in measurements of plate dent, detonation velocity, copper cylinder energy, and detonation pressure. It will be seen from the early and incomplete data presented that performance measured by metal deformation (denting) or by acceleration (cylinder test) can be varied over different ranges while one of the CJ parameters (detonation velocity) changes little and another (detonation pressure) apparently changes much more and not in accordance with the equation above relating P and D unless unusual values and large changes in gamma are postulated.

It is also shown that, in one composite (TNT/AN) the detonation product nitrogen does not mix between fuel and oxidizer at the level predicted from total elemental breakdown in the detonation

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zone demonstrated in other studies with an ideal explosive. The data also lead to a calculation of the thickness of the diffusion zone.

Plate-denting and cylinder performance of some potentially useful eutectic fuel-oxidizer explosive systems based on ethylenediamine dinitrate (EDD) and ammonium nitrate (AN) are given and compared; they differ in response. These are in turn compared to some ideals and standard explosives. Variability in inter-reactivity for unknown reasons, implied by variability in plate-denting, is also related.

The low shock sensitivity of the EDD/AN eutectic system is depicted, with means suggested to raise it while maintaining low mechanical sensitivity. Multicomponent systems can give more control over the several kinds of sensitiviy than unimolecular systems.

Availability and producibility factors are given which show that an industrial base could be used more than at present for bulk-use explosives, while maintaining or improving costs.

Unknowns in nonideal detonation are discussed along with means and plans to experimentally elucidate some of them.

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Thermal Relaxation in Condensed Explosives, E. T. TOTON,
Naval Surface Weapons Center/White Oak. The mechanism of shock-
induced dissociation of explosive molecules in the condensed phase
is investigated. Because of the observed finite reaction times,
it is reasonable to assume that little dissociation is induced by
the shock front itself even though collision times within the
shock zone can be on the order of vibration periods of a
dissociative mode. The internal vibrational modes of the
explosive molecules correspond to the optical modes of the
condensed explosive. Since the internal forces of a molecule
are large compared to the intermolecular forces, the former
will be little affected. The lattice modes are strongly affected
by comparison, however. Calculations based on theoretical
estimates of the Grüneisen parameter for TATB,[1] a particularly
"soft" explosive, indicate an increase of the lattice mode
frequencies of less than an order of magnitude in pressurization
of 130 kilobars. For other explosives the frequency shift will
be substantially less. We assume, then, that the optical band
corresponding to the dissociative mode is characterized by
frequencies large compared to the highest acoustic frequencies
within the compressed explosive.

Following the suggestion of Lin[2] we investigate the optical
and acoustic modes with the Born-Oppenheimer formalism, the optical
dissociative mode corresponding to the fast system. The
assumption is made that the lattice modes are immediately
thermalized at elevated temperature by shock passage and
that the optical modes are initially unexcited. The relaxation
to thermal equilibrium is calculated in a fashion similar to
Krivolgaz[3] for F-center non-radiative transitions using the non-
adiabatic terms occuring in the Born-Oppenheimer formalism.
General features of the relaxation rate are discussed including
under what circumstances long relaxation times might occur.

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NUCLEAR AIR BLAST SIMULATION BY FUEL-AIR EXPLOSION

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ABSTRACT

The progress of an experimental program is reported in which simulation of nuclear airblast by means of fuel-air explosions is being investigated. This program has focused specifically on explosions of hemispherical fuel-air clouds formed from a "point source", using multiple-nozzle liquid fuel injection. The research involves two areas. First is an assessment of the degree of correspondence between FAE and nuclear airblasts in terms of peak and time-resolved static and stagnation pressures, ground impulse, positive-phase duration, and wave front decay rates. A small scale instrumented FAE facility (cloud diameter ∿9m) has been developed for this purpose. The second research area involves examining the engineering requirements for scale-up of this facility to a one kiloton nuclear equivalent. In particular, impulsive liquid fuel injection has been investigated with nozzles ranging from 2-10 cm in diameter. The ultimate vertical reach, degree of atomization, fuel-air distribution, and transverse spreading rate of these jets are considered to be the basic dependent variables, with initial jet velocity, nozzle diameter, nozzle length, quantity of fuel dispensed per nozzle, and fuel properties (density, viscosity, surface tension, and vapor pressure) taken as independent. Current estimates indicate that a one kiloton FAE simulation using propylene oxide would require a hemispherical cloud 142 m in diameter if the global fuel-air ratio were stoichiometric. The individual nozzles that would be required to form this cloud must therefore be capable of injection to 71m.

The experiments with small-scale clouds have demonstrated reasonable nuclear/FAE airblast fidelity. (The experimental facility has been recently improved and testing in this area is continuing.) It has in addition been found that in fuel-air explosions, approximately 50% more of the energy represented by the initial quantity of fuel present is coupled to the air (as thermal and kinetic energy) than in a nuclear explosion of equal yield.

Observations of large diameter impulsively injected liquid jets have indicated that several breakup mechanisms may simultaneously be operative. Breakup at the "head" of the jet appears to result from a recurring Taylor instability, while breakup along the sides of the jet may result from boundary layer stripping or a Helmholtz instability. Due to internal turbulent motion the jet may cease to possess a contiguous core above some height. The "tail" of the jet breaks up in what may be a response to periodic vortex shedding. Material removed from the jet as droplets or strands presumably undergoes successive aerodynamic shattering and subsequent vaporization processes. By these mechanisms fuel vapor is added to the air at all injection radii. Attempts to detonate the two-phase fuel-air column from a single large diameter nozzle have been successful, indicating a combustible mixture can be attained along the full column length.

AN FOE BALLOON SYSTEM FOR NUCLEAR BLAST SIMULATION

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The need for a non-nuclear explosive source that can simulate quantitatively the blast overpressure and impulse of a nuclear weapon at a distance when it is detonated at the surface of the earth is important to those charged with designing defensive military structures, military vehicles, military weapons, etc. Various concepts for such a non-nuclear source have been considered in the past. In this paper, a concept is presented that has some striking advantages. The foremost advantage is that it requires no uncertain basic research; it makes use of known explosion characteristics and requires only straightforward engineering. The second important advantage is that it is the least costly of the various alternatives examined by us, not only in the final full-size system but also in the initial developmental steps that may be needed, from first trial to the final system.

Although the first inclination of the designer might be to scale up the design concept of an existing FAE weapon, that is, to make use of a similar monopropellant fuel (generally liquid), a similar expulsion and dispersion system, and perhaps even a similar type of fuel containment, it becomes evident upon reconsideration that the weapon-configured FAE is not the simplest way to do the job, that the complexities of that type of system can be avoided when there is no need to launch the device. This leads almost directly to a simple balloon-contained oblate-hemispherical body of premixed gas, which for simplicity and cheapness is chosen to be natural gas and oxygen in exact stoichiometric proportions. The exactness of mixture ratio and cloud shape lead to precise control of the resulting blast signature.

Balloons of the size needed to contain a 1 kton fuel-oxygen explosive source (FOE) are commercially available in today's market. (In fact, present large balloons, designed as warehouses, athletic stadiums, etc., are much too rugged for our purpose of one-time use, and yet they are cheap enough for the system.) In the design task, the overpressure and impulse versus distance from ground zero were worked out, and the results will be discussed.

The FOE system is seen as a practical approach to the development of a non-nuclear source that can be used for simulation of nuclear explosives for defense purposes.

OVERVIEW OF DOE's LIQUIFIED NATURAL GAS (LNG) RESEARCH PROGRAM AND RELATED NEEDS

by

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ABSTRACT NOT AVAILABLE

OVERVIEW OF US COAST GUARD'S RESEARCH PROGRAM
ASSOCIATED WITH UNCONFINED FUEL-AIR EXPLOSIONS

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ABSTRACT NOT AVAILABLE

UNCONFINED AND SEMI-CONFINED FUEL-AIR
EXPLOSIONS ON INDUSTRIAL SITES

BY

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Analysis of reported accidental FAE incidents has continued along the lines
of defining the different factors which influence the effect on ignition. These
relate to the combustion character of the fuel, the conditions under which it
was contained, the mechanism of release, the position of release relative to
the surroundings, atmospheric conditions and the location of effective
ignition sources.

A number of these factors are difficult to handle as regards the influence
they have on the fuel-air explosion behaviour, but conclusions can be drawn
regarding others.

The first conclusion is that no sizeable accidental FAE's have been discovered
as having occurred during high wind conditions. A highly turbulent atmosphere
appears to disperse the fuel without giving it effective contact time with
potential ignition sources.

Secondly, where the accidental fuel release is the result of an internal
combustion or other reaction, the released fuel is at an elevated temperature
and contains a concentration of free radicals derived from the internal reaction
such that the ignition delay is short. (Also the ignition can be characterised
as multipoint where the blast effects approach that of a bursting pressurised
sphere.)

Thirdly, fuels can be divided into four categories according to their
combustion character. The autodecomposible fuel category (acetylene etc)
is followed by a category typified by ethylene where the damage record is
significantly more severe than the normal fuel category. Lastly there is
a sub-normal fuel category containing pure methane, ammonia, methylene
chloride etc for which no explosive behavioural incidents have been found.

Fourthly and most important, are the mechanism of release, the release position
relative to the surroundings and atmospheric conditions. These determine how
the fuel mixes with air and its movement in the atmosphere once a fuel-air
cloud is formed. The conditions under which the fuel had been contained and
its pressure-temperature characteristics frequently determine if the cloud
is predominantly a mist and whether it is dense or light compared to the
atmosphere.

Finally, we have the influence of potential ignition sources. These are
minimal in non-built up areas and differ in nature between industrial and
residential areas. The result is that cloud drift tends to be larger in the
more open areas, but that the larger time delay before ignition decreases
the turbulence level in the cloud.

These factors have been incorporated where possible into the predictive method for overall blast plus fire damage. Also incorporated has been the effect of a low level of flammable material release from the structures and buildings exposed to the blast.

The case of the spillage of large quantities of fuel has been examined and the possibility of a fire being followed by an aerial explosion at a considerable height is discussed.